

EVLA OBSERVATIONS CONSTRAIN THE ENVIRONMENT AND PROGENITOR SYSTEM OF TYPE IA SUPERNOVA 2011FE

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ABSTRACT

We report unique EVLA observations of SN 2011fe representing the most sensitive radio study of a Type Ia supernova to date. Our data place direct constraints on the density of the surrounding medium at radii $\sim 10^{15} - 10^{16}$ cm, implying an upper limit on the mass loss rate from the progenitor system of $\dot{M} \lesssim 6 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ (assuming a wind speed of 100 km s^{-1}), or expansion into a uniform medium with density $n_{\text{CSM}} \lesssim 6 \text{ cm}^{-3}$. Drawing from the observed properties of non-conservative mass transfer among accreting white dwarfs, we use these limits on the density of the immediate environs to exclude a phase space of possible progenitors systems for SN 2011fe. We rule out a symbiotic progenitor system and also a system characterized by high accretion rate onto the white dwarf that is expected to give rise to optically-thick accretion winds. Assuming that a small fraction, 1%, of the mass accreted is lost from the progenitor system, we also eliminate much of the potential progenitor parameter space for white dwarfs hosting recurrent novae or undergoing stable nuclear burning. Therefore, we rule out much of the parameter space associated with popular single degenerate progenitor models for SN 2011fe, leaving a limited phase space largely inhabited by some double degenerate systems, as well as exotic single degenerates with a sufficient time delay between mass accretion and SN explosion.

Subject headings: supernovae: individual (SN 2011fe) — supernovae: general — novae, cataclysmic variables — binaries: general — circumstellar matter

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are luminous stellar explosions that display remarkable homogeneity in their optical properties. Comprising $\sim 30\%$ of all SNe in the local universe (Li et al. 2011a), SNe Ia are exploited as beacons for cosmography and represent the dominant source of iron-peak elements; however, we still do not understand the nature of their progenitor system(s). There is a general consensus that SNe Ia mark the fatal disruption of white dwarfs (WDs) near the Chandrasekhar limit ($M_{\text{Ch}} = 1.4 M_{\odot}$), and accretion from a binary companion is required to reach sufficient WD mass and trigger the SN explosion (Hillebrandt & Niemeyer 2000). However, the nature of this binary companion remains unclear, with potential progenitor systems falling into two broad classes: single degenerate (SD; containing a WD and a main-sequence, sub-giant, He star, or red-giant companion star; Whelan & Iben 1973; Nomoto 1982), and double degenerate (DD; in which two WDs merge; Webbink 1984; Iben & Tutukov 1984). In both scenarios, the evolution of the progenitor system shapes the circumbinary environment.

Radio observations provide a sensitive probe of cir-

cumstellar material (CSM) surrounding SNe; when the shockwave plows into this material, it accelerates particles and amplifies the magnetic field, producing synchrotron emission that peaks in the cm band (Chevalier 1982b). The early synchrotron signal traces the CSM particle density, n_{CSM} , on a radial scale of $\lesssim 1$ pc, the region shaped by the final stage of progenitor evolution. Radio emission is routinely detected from nearby ($d_L \lesssim 10$ Mpc) core-collapse SNe (Weiler et al. 2002)—explosions that mark the death of massive stars, $M \gtrsim 8 M_{\odot}$ (Smartt 2009). However, radio emission has never been detected from a young SN Ia, despite searches spanning the past three decades (Panagia et al. 2006; Hancock et al. 2011).

On 2011 August 24 UT, the Palomar Transient Factory (PTF; Law et al. 2009) discovered an optical transient within the nearby spiral galaxy M101 at a distance of 6.4 Mpc (Shappee & Stanek 2011; Figure 1). Based on pre- and post-discovery imaging, the explosion date is well constrained to 2011 Aug 23.69 UT (Nugent et al. 2011). Early optical spectroscopy revealed the transient to be a SN of the hydrogen-poor Type Ia class (Nugent et al. 2011), the nearest such event discovered in 25 years, dubbed SN 2011fe (PTF11kly). Detailed optical studies indicate that SN 2011fe is photometrically (Nugent et al. 2011; Margutti et al. 2012) and spectroscopically (Parrent et al. 2012, in preparation) a normal Type Ia.

Here we present deep Expanded Very Large Array (EVLA) radio observations of SN 2011fe, obtained just two days after explosion and enabling a factor of ten improvement in sensitivity over previous limits. We note that radio observations of SN 2011fe were recently reported by Horesh et al. (2012); however, our data are significantly deeper and span a longer timescale. We pro-

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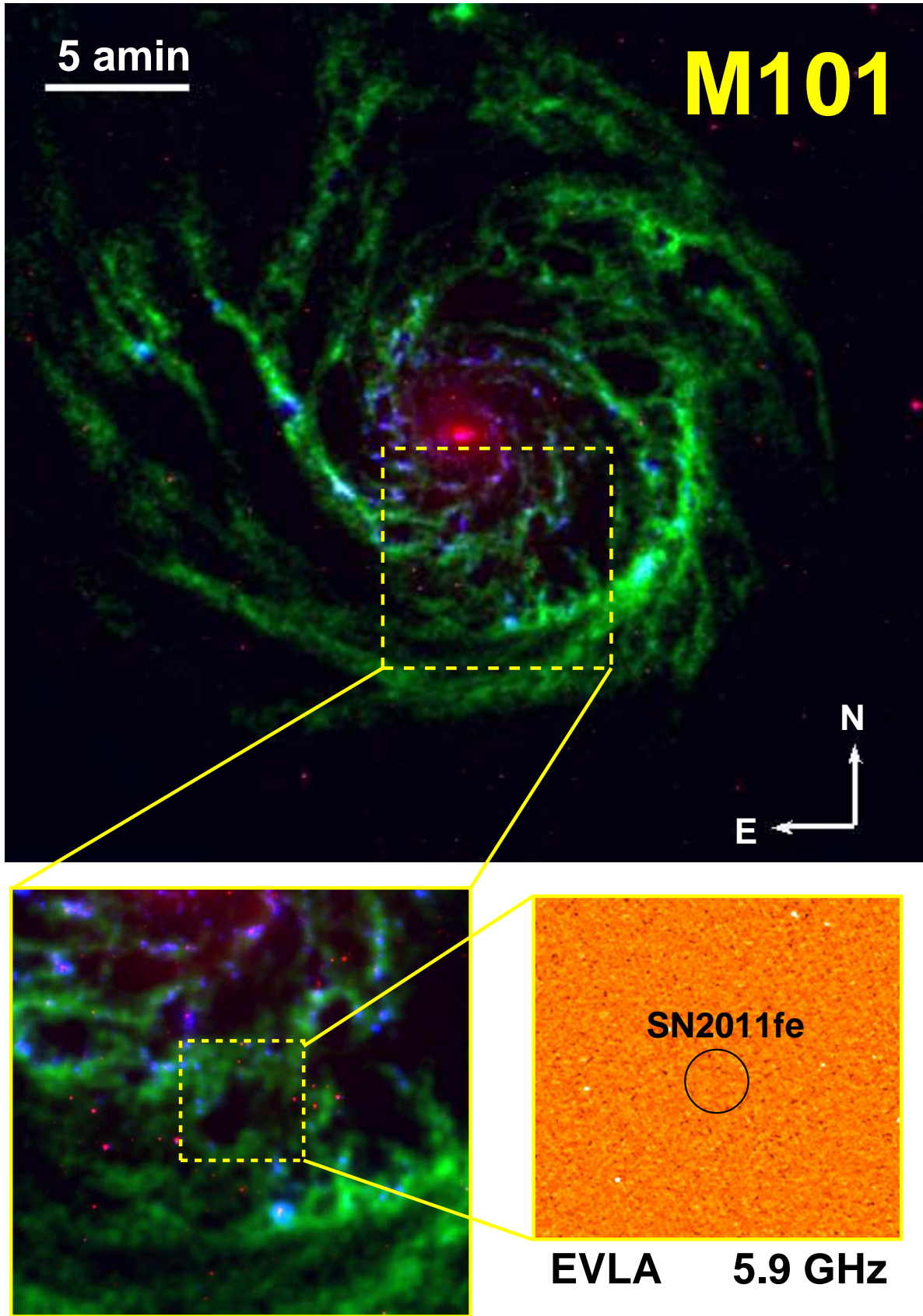


FIG. 1.— Images of the environs of SN 2011fe. The three-color image of the host galaxy, M101, features 21 cm emission (green; Walter et al. 2008) tracing neutral hydrogen, $H\alpha$ emission (blue; Hoopes et al. 2001) tracing star formation, and $3.6\ \mu\text{m}$ emission (red; Dale et al. 2009) tracing the stellar mass. The bottom left image shows detail of the explosion site of SN 2011fe, while the bottom right image shows our combined EVLA image at 5.9 GHz centered on the SN position (black circle has a radius of 10 arcsec).

vide a theoretical analysis of the data that and a fresh perspective on the relation between radio luminosity and CSM density around SNe Ia. We discuss our observations and interpret the measured upper limits in Sections 2 and 3, and then consider the implications for a wide range of SN Ia progenitor scenarios and previous observations in Sections 4, 5, 6, and 7.

2. OBSERVATIONS

We initiated radio observations of SN 2011fe on 2011 Aug 25.8 UT ($\Delta t \approx 2$ days after explosion) with the EVLA (Perley et al. 2011) under our program AS1015 (PI Soderberg; Chomiuk & Soderberg 2011). No radio counterpart was detected at the optical SN position to a limit, $F_\nu \lesssim 19 \mu\text{Jy}$ (3σ ; Figure 2). We continued observations of SN 2011fe through our Director’s Discretionary Time program 11B-217 (PI Soderberg) over six epochs that span three weeks following the explosion, as described in Table 1. Our subsequent EVLA observations reveal similar upper limits (Figure 2). Observations were carried out in A configuration using 2 GHz of bandwidth and recording four polarization products; one baseband of 1 GHz width was centered at 5.0 GHz while the other was centered at 6.75 GHz. Each epoch had one hour duration, yielding 40 minutes on source, except 2011 Aug 26, when we observed for two hours. Data were calibrated using J1349+5341 and 3C286, and were reduced using standard routines in the Astronomical Image Processing System (AIPS). Each sideband was imaged individually; the 6.75 GHz image was then smoothed to the resolution of the 5.0 GHz image, and the two noise-weighted images were averaged together. We also created a stacked image by concatenating all uv data for a given sideband and producing a final image from the combined data set. Again, the two sidebands were averaged together in the image plane, producing an image that reaches the thermal noise limit at 5.9 GHz. Our stacked EVLA data place a strong constraint on the radio luminosity of $L_\nu \lesssim 3.2 \times 10^{23} \text{ erg s}^{-1} \text{ Hz}^{-1}$ on an averaged date of 9.1 days after explosion (Figure 1).

The resolution of our EVLA images is $0.56'' \times 0.39''$. The flux densities quoted in Table 1 are measured at the SN coordinates given by Li et al. (2011b). The nearest point displaying any significant flux in our stacked image is a 4.5σ ($10.2 \mu\text{Jy}$ at maximum) point-like peak located $0.7''$ away from the Li et al. (2011b) position (at J2000.0 RA = $14^{\text{h}}03^{\text{m}}05.799^{\text{s}}$, Dec = $+54^\circ16'24.75''$). However, when we image the RR and LL correlations of the EVLA polarizations separately, we find that no source is visible in the RR image ($3 \pm 3 \mu\text{Jy}$ in RR, as opposed to $16 \pm 3 \mu\text{Jy}$ in LL), thus implying that it is likely an instrumental artifact, and unlikely to be a real source. We also investigated if the position of the radio peak could possibly be consistent with SN 2011fe by checking the world coordinate systems of our EVLA image and the *HST* ACS/F814W image (GO-9490, PI K. Kuntz) used by Li et al. (2011b) for consistency. We cross-compared the positions of two compact H II regions located $\sim 1.5'$ northeast of SN 2011fe that are visible in both the *HST* and EVLA images. For this comparison, we also made use of a narrow-band H α image from *HST*/WFPC2 (GO-5210, PI J. Trauger), as these H II regions are much more clearly defined in F656N than in F814W. We find that the coordinate systems are not offset by more than $0.2''$,

TABLE 1
EVLA OBSERVATIONAL DATA FOR SN 2011FE

Date (UT)	Flux Density (μJy)	Time Since Explosion (Days)
2011 Aug 25.77	7.8 ± 5.8	2.1
2011 Aug 27.72	0.4 ± 6.1	4.0
2011 Aug 29.98	-8.4 ± 6.9	6.3
2011 Sept 2.68	0.7 ± 4.3	9.0
2011 Sept 8.04	-2.7 ± 6.6	14.4
2011 Sept 12.93	0.6 ± 6.0	19.2
Stacked: Aug 25.8–Sept 12.9	-0.6 ± 2.2	2.1–19.2

and thus the 4.5σ radio peak is positionally inconsistent with SN 2011fe.

3. DENSITY CONSTRAINTS FROM RADIO UPPER LIMITS

We make predictions for the radio emission from SNe Ia by analogizing them to other hydrogen-poor SNe which are detected in the radio, namely Type Ib and Type Ic SNe (SNe Ibc; e.g., Berger et al. 2003; Chevalier & Fransson 2006; Soderberg et al. 2010). SNe Ibc are generally understood to mark the gravitational core collapse of massive stars that have been stripped of their hydrogen envelopes prior to explosion. The analogy between SNe Ia and Ibc is motivated by several commonalities, including (i) their compact progenitors, leading to mildly-relativistic shockwaves at the time of breakout from the star (Colgate 1970; Nakar & Sari 2012), and (ii) a common polytrope of $\gamma = 4/3$, appropriate for both massive (relativistic) WDs and the radiative envelopes of Wolf-Rayet stars. It is estimated that for SNe arising from compact progenitors, the outermost density profile of the ejecta (hosting the fastest moving material, which gives rise to the radio emission) is characterized by a steep power-law, $\rho_{\text{SN}} \propto r^{-10.2}$; (Matzner & McKee 1999). The coupling of mass to ejecta velocity is simply a function of the bulk explosion energy (E_{51} , in units of 10^{51} erg) and ejecta mass (M_{ej} ; Berger et al. 2002; Chevalier & Fransson 2006). These parameters are well constrained in the case of SNe Ia; $E_{51} = 1$ and $M_{\text{ej}} = M_{\text{ch}} = 1.4 M_\odot$ are fiducial values (Mazzali et al. 2007).

The interaction of the shockwave with the immediate environment is then described by a self-similar solution, such that the evolution of the shockwave radius (R_s) and its velocity (v_s) are determined by the properties of the environment: its particle density (n_{CSM}) and its radial profile (Chevalier 1982a). This dynamical interaction accelerates particles from the circumstellar environment into a power-law energy distribution, $N(E) = N_0 E^{-p}$, where $N(E)$ is the density of relativistic electrons at a given energy E , above a minimum energy, E_m . We further assume that constant fractions of the post-shock energy density is shared between relativistic electrons (ϵ_e) and amplified magnetic fields (ϵ_B) and a shock compression factor, $\eta = 4$ (Chevalier & Fransson 2006). In this framework,

$$B = \sqrt{8\pi \epsilon_B \rho_{\text{CSM}} v_s^2}, \quad (1)$$

$$N_0 = (p - 2) \epsilon_e \rho_{\text{CSM}} v_s^2 E_m^{p-2}, \quad (2)$$

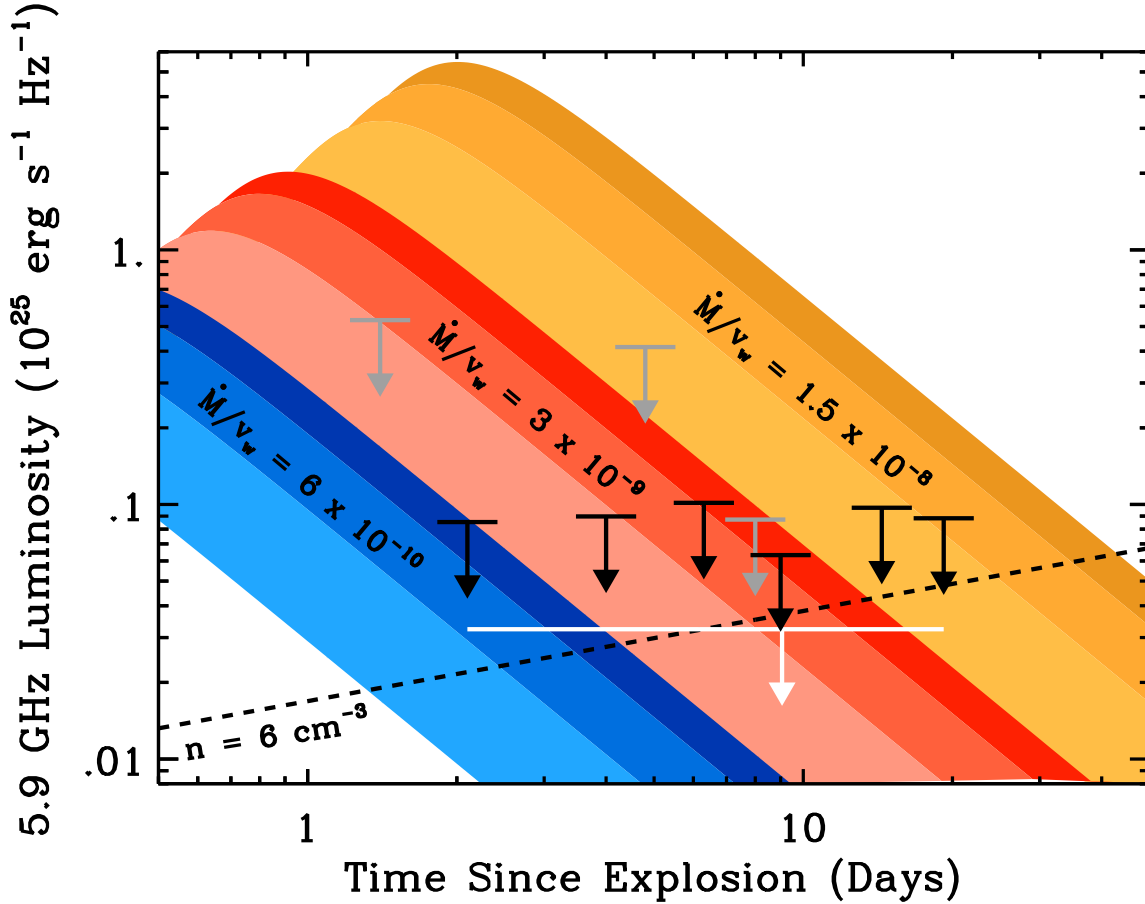


FIG. 2.— Deep limits on the radio luminosity of SN 2011fe. Our 5.9 GHz upper limits (black arrows; 3σ) from six EVLA epochs are compared with model light curves for three different progenitor wind mass loss rates: $\dot{M}/v_w = 1.5 \times 10^{-8} \frac{M_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (gold); $3 \times 10^{-9} \frac{M_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (red); $6 \times 10^{-10} \frac{M_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (blue). Each swath spans $\epsilon_B = 0.01 - 0.1$ (with the intermediate boundaries between shades corresponding to $\epsilon_B = 0.033$ and 0.066) and assumes $\epsilon_e = 0.1$, $M_{\text{ej}} = 1.4 M_\odot$, and $E_K = 10^{51}$ erg. We also plot our stacked limit as a white arrow, used to constrain a model for uniform-density CSM with a particle density of $\lesssim 6 \text{ cm}^{-3}$ (for $\epsilon_B = 0.1$; dashed black line). Finally, overplotted as grey arrows are additional data from Horesh et al. (2012), scaled to 5.9 GHz.

and

$$E_m = \frac{(p-2)\epsilon_e \mu m_p v_s^2}{(p-1)\eta(n_e/n_i)}. \quad (3)$$

Here μ is the mean molecular weight of the CSM assuming it is neutral, and (n_e/n_i) is the number ratio of electrons to ions in the shocked gas (for solar abundance, $\mu = 1.4$ and $n_e/n_i = 1.14$). The shock-accelerated electrons gyrate along the magnetic field lines, giving rise to synchrotron radiation that peaks in the radio shortly after explosion with a spectrum, $L_\nu \propto \nu^\beta$; here $\beta = -(p-1)/2$. The high velocity shockwaves of Type I SNe minimize opacity to external free-free absorption, such that synchrotron self-absorption dominates the spectral energy distribution, suppressing the emission at low frequencies (Chevalier 1998). For sources characterized by synchrotron self absorption, the shock radius may be robustly inferred from the synchrotron light curve (Readhead 1994), thus enabling a direct tie between the observed radio properties and the SN self-similar solution (Chevalier 1998).

For SN 2011fe, we assume $p = 3$, $\epsilon_e = 0.1$,

and a range of $\epsilon_B = [0.01 - 0.1]$ as inferred for SN Ib/c (Chevalier & Fransson 2006; Zhang et al. 2009; Soderberg et al. 2011). In this framework, the radio luminosity at a given frequency and time after explosion depends only on n_{CSM} , and is calculated using Equation 1 of Chevalier (1998). Therefore, radio observations probe the environment of SNe Ia and may distinguish between different progenitor systems (see Chomiuk et al. 2012, in preparation, for a detailed discussion).

3.1. Wind Density Profile for the CSM

A commonality among SD progenitor channels is the accretion of material onto a WD due to its interaction with a donor star. While possible progenitor scenarios span a wide parameter space (Hillebrandt & Niemeyer 2000), most scenarios may be characterized by the WD's accretion rate, \dot{M}_{acc} , and efficiency of accretion, ϵ_{acc} , such that the rate of mass lost into the local environs is $\dot{M}_{\text{loss}} = (1 - \epsilon_{\text{acc}})\dot{M}_{\text{acc}}$ (Nomoto et al. 2007). Here we define, $\epsilon_{\text{loss}} = (1 - \epsilon_{\text{acc}})$. In this non-conservative mass transfer scenario, we assume that the lost material

is blown outward with a wind velocity, v_w , and radially distributed as $n_{\text{CSM}} = \dot{M}/(4\pi v_w r^2)$.

Using the similarity solutions of Chevalier (1982a) and the SN Ia ejecta density profile of Chomiuk et al. (2012, in preparation), we estimate the shockwave radius to be:

$$R_s = 5.5 \times 10^{14} (\dot{M}/v_w)^{-0.12} E_{51}^{0.43} M_{\text{ch}}^{-0.31} t_{10}^{0.88} \text{ cm}, \quad (4)$$

where t_{10} is the time since explosion in units of 10 days. For $t_{10} = 0.21$, $\dot{M}/v_w = 10^{-10} \frac{M_{\odot} \text{ yr}^{-1}}{\text{km s}^{-1}}$, $E_{51} = 1$, and $M_{\text{ch}} = 1$, we find $R_s = 2.2 \times 10^{15}$ cm and the shockwave velocity ($v_s = 0.88 R_s/t$) is $0.35c$.

When the SN shockwave interacts with such a medium, the radio emission is suppressed at early times by synchrotron self absorption, and declines at later times due to the decelerating shockwave and decreasing density of the CSM. With the radius evolution and assumptions described above, we calculate a family of radio light curves using the formalism of Chevalier (1998) and Chevalier & Fransson (2006). In the optically-thin regime (after light-curve peak, which is valid here; Figure 2), for a given luminosity limit, our constraint on \dot{M}/v_w scales as $\epsilon_B^{-0.7}$.

Our measured upper limits on L_{ν} measured $\Delta t \approx 2.1$ days after explosion provide the deepest limits on the density of the environment surrounding SN 2011fe to date, corresponding to $\dot{M}/v_w \lesssim 6 \times 10^{-10} \frac{M_{\odot} \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (assuming $\epsilon_B = 0.1$) or $\dot{M}/v_w \lesssim 3 \times 10^{-9} \frac{M_{\odot} \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (assuming $\epsilon_B = 0.01$) for the SN 2011fe progenitor system. These limits are a factor of ~ 20 deeper than those presented by Horesh et al. (2012), due to our calculation from first principles of v_s and our self-consistent treatment of E_m .

Mass loss from a SD progenitor may be concentrated toward the equatorial or polar regions of the orbit (e.g., Mohamed & Podsiadlowski 2011). Assuming that the asymmetric mass loss still follows an $n_{\text{CSM}} \propto r^{-2}$ radial profile, and covers a solid angle Ω (units of steradians), the radio luminosity scales as $L_{\nu} \propto (\frac{\Omega}{4\pi})^{-0.4}$. The increase in CSM density due to asymmetry wins out over the slightly stronger deceleration of the shockwave, leading to an increase in the radio luminosity for a given \dot{M}/v_w , if material is expelled asymmetrically. Therefore, our assumption of spherical symmetry is conservative.

3.2. Uniform Density Profile for the CSM

We also consider a uniform density medium, as might be expected if the SN is exploding into the ambient interstellar medium. In this case, again using the similarity solutions from Chevalier (1982a) and the density profile of SN Ia ejecta from Chomiuk et al. (2012, in preparation), the SN shockwave radius evolves as:

$$R_s = 1.4 \times 10^{16} n_{\text{CSM}}^{-0.10} E_{51}^{0.35} M_{\text{ch}}^{-0.25} t_{10}^{0.71} \text{ cm}. \quad (5)$$

For $t_{10} = 0.21$, $n_{\text{CSM}} = 1 \text{ cm}^{-3}$, $E_{51} = 1$, and $M_{\text{ch}} = 1$, we calculate $R_s = 4.5 \times 10^{15}$ cm and a shockwave velocity ($v_s = 0.71 R_s/t$) of $0.58c$. The radio light curve in the case of a uniform density medium is relatively flat, as compared the wind density profile (Figure 2), so the most powerful observational constraint comes from our stacked limit, giving a density limits in the range $n_{\text{CSM}} \lesssim 6 \text{ cm}^{-3}$

($\epsilon_B = 0.1$) to $n_{\text{CSM}} \lesssim 44 \text{ cm}^{-3}$ ($\epsilon_B = 0.01$). Here, our limits on the density scale with the assumed value for ϵ_B as $n_{\text{CSM}} \propto \epsilon_B^{-0.9}$. It is noteworthy that, unlike in the wind case, the radio luminosity actually increases with time, because the decline in post-shock energy density is more gradual. In this uniform density case, the growth in the radio-emitting volume overwhelms the effects of gradual deceleration of the shockwave, implying that the total energies in magnetic fields and relativistic electrons slowly grow as the SN expands.

4. IMPLICATIONS FOR SN IA PROGENITORS

Below, we compare these constraints on the environment of SN 2011fe with predictions for popular single degenerate scenarios, summarized in Figure 3.

Symbiotic Systems: In the first SD scenario, the SN 2011fe progenitor system consists of a WD in a symbiotic binary system, accreting mass from a giant star (Figure 3). Mass is lost from the system at a rate $\dot{M} > 10^{-8} M_{\odot} \text{ yr}^{-1}$ with velocity $v_w \approx 30 \text{ km s}^{-1}$ (Sequist & Taylor 1990; Patat et al. 2011a; Chen et al. 2011). This model is ruled out by our EVLA observations and is consistent with the non-detection of a giant star in pre-explosion optical imaging (Li et al. 2011b) and X-ray limits on the inverse Compton emission from the shockwave (Horesh et al. 2012, Margutti et al. 2012).

White Dwarfs with Steady Nuclear Burning: Next, we consider a main sequence, subgiant, or helium star undergoing stable Roche Lobe overflow onto a WD. For accretion rates of $\dot{M}_{\text{acc}} \gtrsim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, the WD will undergo steady nuclear burning (Shen & Bildsten 2007). We assume that a small fraction of the transferred mass ($\epsilon_{\text{loss}} \approx 1\%$) is lost at the outer Lagrangian points of the system and travels outwards at at some factor of order unity of the orbital velocity, $v_w \approx 100 \text{ km s}^{-1}$ (dark blue region in Figure 3). This mode of outer Lagrangian mass loss with velocities up to $\sim 600 \text{ km s}^{-1}$ has been manifested in the P-Cygni profiles of stable nuclear burning WDs undergoing these moderate accretion rates (Deufel et al. 1999). This scenario is also supported by the circumbinary material observed from cataclysmic variable systems (Williams et al. 2008), as well as the steady orbital separations measured in long period cataclysmic variables (Huang & Yu 1996). Most of this parameter space is ruled out for SN 2011fe by our EVLA limits, in the $\epsilon_B = 0.1$ case.

At higher mass transfer rates, optically-thick winds in the vicinity of the WD are hypothesized to limit the mass accretion to $\dot{M}_{\text{acc}} \approx 6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, and any additional mass transferred is lost from the system with velocity, $v_w \approx \text{few} \times 1,000 \text{ km s}^{-1}$ (light blue region in Figure 3; Hachisu et al. 1999), consistent with outflows seen in the most X-ray luminous nuclear burning WDs (Cowley et al. 1998). This scenario is completely excluded by our EVLA limits if the accretion wind immediately preceded the SN explosion (see §6.1 for further discussion).

Near the transition point between these moderate and high accretion rate regimes, spectroscopic analysis of the absorption profiles of luminous nuclear-burning WDs reveals that the mass loss rate is $\sim 10\%$ the accretion rate, or $3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$, and is expelled at a high velocity of $v_w = 3,000 \text{ km s}^{-1}$ (Murray 2002). Such a high-velocity

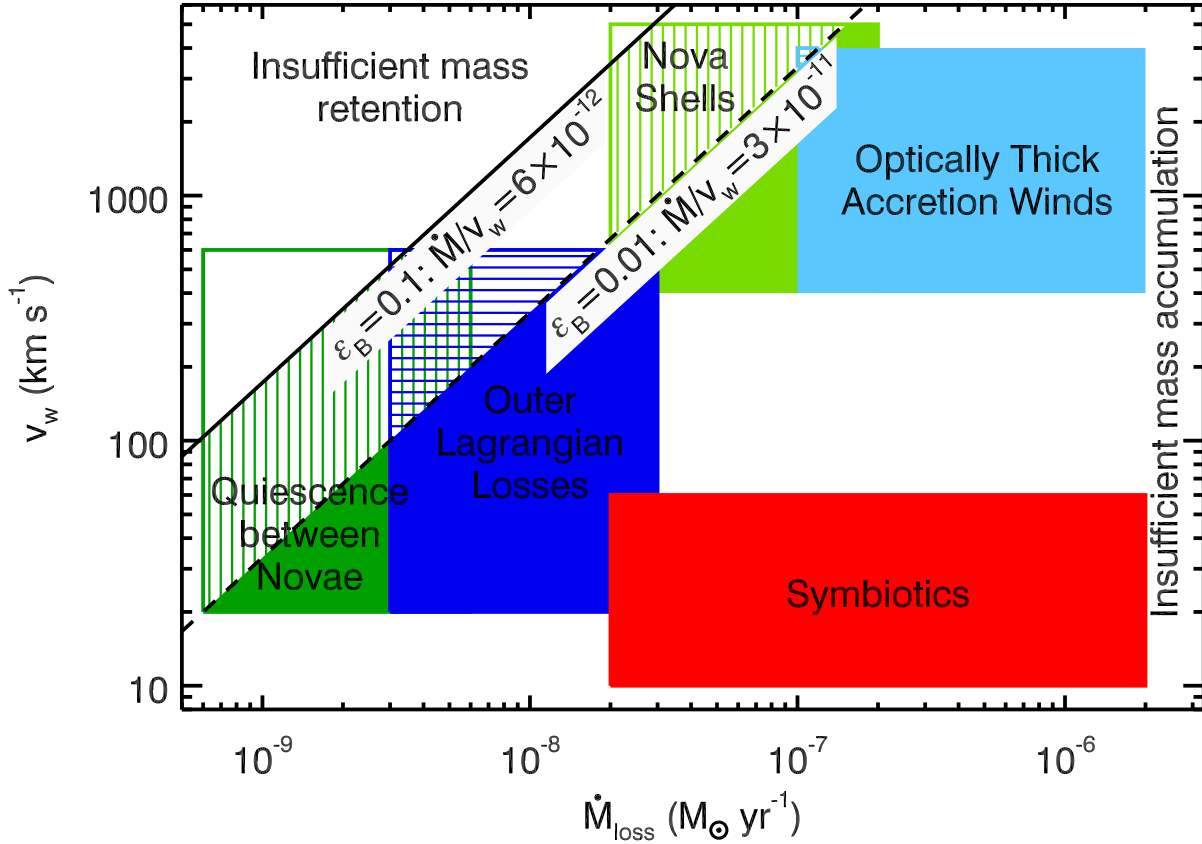


FIG. 3.— Constraints on the parameter space of mass loss rate from the binary system versus the velocity of the lost material. The progenitor scenarios discussed in Section 4 are plotted as schematic zones in \dot{M} - v_w space. We indicate our 3σ limits on \dot{M}/v_w assuming $\epsilon_B = 0.1$ (solid; corresponding to the dark blue curve in Figure 2), and the conservative case of $\epsilon_B = 0.01$ (dashed; corresponding to the light red curve in Figure 2). Mass loss scenarios to the lower right of these lines would have been detected with our EVLA observations, and are eliminated for SN 2011fe. At the lowest mass accretion rates, nova eruptions will expel the accreted material, and there will be insufficient mass retention toward SNe Ia. At high mass transfer rates $\gtrsim 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$, too much mass is lost though winds, so that the WD will not accrete sufficient mass to approach M_{Ch} .

accretion wind would have been barely detectable by our radio data (assuming $\epsilon_B = 0.1$, see Fig. 3); nevertheless, the slower wind via the outer Lagrangian points, albeit intrinsically lower in its mass loss rate, would have been readily detectable due to the high accretion rate in such a system.

Our EVLA observations of SN 2011fe therefore critically constrain stable nuclear burning in both accretion regimes (outer Lagrangian losses and optically-thick winds; Figure 3). Parallel studies based on pre-explosion X-ray images of the SN 2011fe progenitor system only rule out a subset of these systems with the most compact and hottest photospheres (Li et al. 2011b; Liu et al. 2011).

Recurrent Novae: Finally, at lower accretion rates, $\dot{M}_{\text{acc}} \approx (1 - 3) \times 10^{-7} M_\odot \text{ yr}^{-1}$, the WD may undergo nova outbursts with a short recurrence time of several years. The nova shells expand with velocities of $1,000 - 5,000 \text{ km s}^{-1}$, leaving evacuated cavities between the shells (Wood-Vasey & Sokoloski 2006). In the paradigm of synchrotron emission produced by the interaction of SN shock with CSM (Chevalier 1982b), ra-

dio emission will be generated when the SN shockwave crashes through a previously ejected shell.

For SN 2011fe, our EVLA observations probe a circumbinary scale of $r \approx 10^{16} \text{ cm}$, thus constraining the presence of shells from novae with short recurrence time, \sim few years. The light green zones in Figure 4 show the distribution of CSM around a nova with recurrence time of 2 years. Models of such a system show that $2 \times 10^{-7} M_\odot \text{ yr}^{-1}$ is incident upon the WD (Yaron et al. 2005; Shen & Bildsten 2009); we assume that 1% of this transferred material is lost to the binary to form the CSM at small radii. During a nova explosion, for the adopted accretion rate onto a $\sim 1.4 M_\odot$ WD, models imply that $\sim 15\%$ of the material accreted over the last two years is ejected in a shell with a mass of $6 \times 10^{-8} M_\odot$ (light green region in Figure 3). Adopting a shell thickness of $\sim 0.1R$, the radio emission is likely short-lived (\sim days) and we estimate a $\sim 30\%$ probability of radio detection of such nova shells in our EVLA data.

For longer recurrence times, the progenitor wind may enhance the local CSM density between eruptions (e.g., U Sco; recurrence timescale of ~ 10 years). The dark

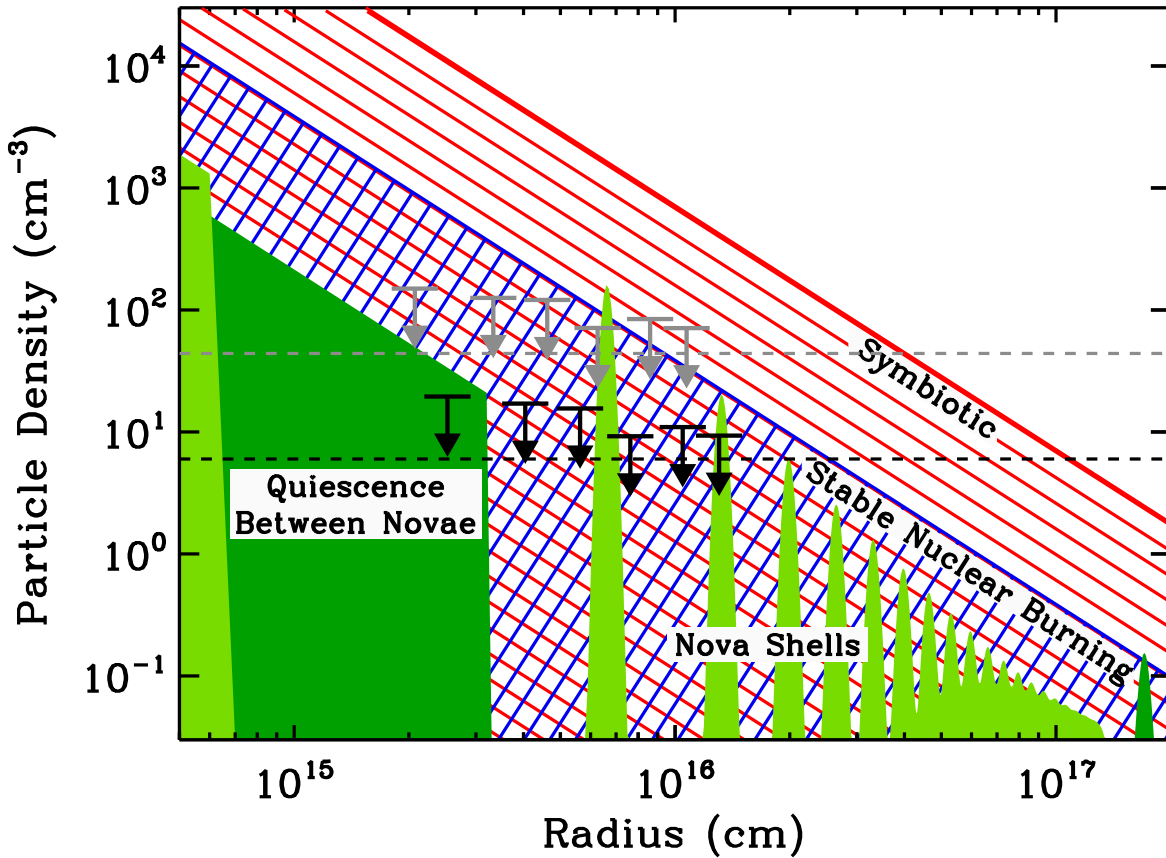


FIG. 4.— Theoretical CSM radial density profiles are estimated for four possible SD progenitor scenarios. *Red*: a symbiotic progenitor system with $\dot{M} = 1 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ and $v_w = 30 \text{ km s}^{-1}$; *Blue*: stable nuclear burning, for either outer Lagrangian losses ($\dot{M} = 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ and $v_w = 100 \text{ km s}^{-1}$) or optically-thick winds ($\dot{M} = 2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ and $v_w = 1,000 \text{ km s}^{-1}$); and *Green*: a recurrent nova system with short recurrence timescale (2 years; light) and longer recurrence timescale (10 years; dark). Assuming a $n_{\text{CSM}} \propto r^{-2}$ CSM density profile, we estimate the CSM densities and shockwave radii that would correspond to our 5.9 GHz limits, for $\epsilon_B = 0.1$ (black arrows) and $\epsilon_B = 0.01$ (grey arrows). Also overplotted are limits for uniform density surroundings, again for $\epsilon_B = 0.1$ (black dashed line) and $\epsilon_B = 0.01$ (grey dashed line).

green regions plotted in Figure 4 represent a nova with recurrence time of 10.3 years, modeled after U Sco. In the case of U Sco, a nova ejecta mass of $10^{-6} M_{\odot}$ is expelled every ~ 10 years at a velocity of $5,000 \text{ km s}^{-1}$ (Hachisu et al. 2000; Schaefer 2010; Diaz et al. 2010). Between eruptions, mass is transferred to the WD at a rate $\dot{M}_{\text{acc}} = 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Duschl et al. 1990; Hachisu et al. 2000). Again, we assume $\epsilon_{\text{loss}} \approx 1\%$ of this transferred mass is lost through the outer Lagrangian points in a wind expelled at roughly the orbital velocity, $v_w = 100 \text{ km s}^{-1}$ (dark green region in Figure 3). The local density is therefore $\dot{M}/v_w = 1 \times 10^{-9} \frac{\epsilon_{\text{loss}} M_{\odot} \text{ yr}^{-1}}{0.01 \text{ } 100 \text{ km s}^{-1}}$, and comparable to our EVLA detection limits (Figure 4) but undetectable in pre-explosion optical images (Li et al. 2011b).

Our assumed ejected and accreted masses for U Sco are intermediate in the uncertain range of estimates in the literature; for example, measurements of the ejecta mass could be a factor of three higher or lower (Evans et al. 2001; Diaz et al. 2010), and estimates of the accretion rate are model dependent. These uncertainties under-

line our point that we can not conclusively rule out a U Sco-like progenitor for SN 2011fe, although we can constrain the large potential parameter space for U Sco-like progenitors.

5. ESTIMATES OF THE BROADER ENVIRONMENT OF SN 2011FE

Alternatively, if SN 2011fe is the result of a DD progenitor system, it may have exploded into an undisturbed and constant density environment. As shown in Figure 1, we can probe the ambient interstellar medium in the $\sim 0.3 \text{ kpc}$ region surrounding the SN explosion site using pre-explosion H I 21 cm imaging from The H I Neary Galaxy Survey (THINGS; Walter et al. 2008). We measure an integrated brightness temperature of $165.4 \text{ K km s}^{-1}$ at the location of SN 2011fe, corresponding to a H I column density of $3.02 \times 10^{20} \text{ cm}^{-2}$. Assuming a path length of 100 pc through the face-on neutral disk of M101 and solar abundance, we roughly estimate a volume number density of $\sim 1 \text{ cm}^{-3}$ at this location, typical of the warm phase of the interstellar medium (Ferrière 2001). Our stacked EVLA limits, which imply $n_{\text{CSM}} \lesssim (6 - 44)$

cm^{-3} , are therefore consistent with expansion into the ambient ISM.

Using $\text{H}\alpha$ imaging as a tracer of star formation in M101, we can also compare the location of SN 2011fe relative to the host galaxy's light distribution. We adopt the methodology for calculating a fractional flux value from Fruchter et al. (2006) and Kelly et al. (2008). We obtain an $\text{H}\alpha$ narrow-band image of the field from Hoopes et al. (2001) with a central wavelength of 6564 Å, and calculate the fraction of total host light in pixels fainter than the SN position. To determine an appropriate cut-off level for the host, we create an intensity histogram of a $30' \times 30'$ region centered on M101 and model the sky brightness distribution with a Gaussian profile, taking pixels with flux above 3σ to be part of M101. We then calculate the flux in galaxy pixels fainter than the location of SN 2011fe and normalize by the total galaxy flux. This gives a fractional flux value of 0.55, showing that SN 2011fe originates from an ordinary region in a star-forming galaxy, consistent with results for other SNe Ia (Kelly et al. 2008). This result affirms that SN 2011fe exploded in a typical environment for a SN Ia, and is not closely associated with a young stellar population (in contrast, SNe Ic and long gamma-ray bursts, which are thought to closely follow star formation, typically have significantly higher fractional fluxes than SNe Ia).

6. DISCUSSION

6.1. Constraints on the Environments of SNe Ia

Here we consider our characterization of the SN 2011fe environment in the context of other multi-wavelength studies of SN Ia environs.

The interaction of a SN shockwave with surrounding CSM should also produce X-ray and $\text{H}\alpha$ emission, along with the radio emission described in detail here. To date, searches for this emission from SNe Ia have yielded only non-detections, although they typically place weaker constraints on the CSM density than radio limits (however, Margutti et al. 2012 have recently shown that deep X-ray observations obtained at optical peak have the potential to surpass radio constraints). Early-time deep $\text{H}\alpha$ observations of SN 2001el constrain the mass loss rate of the progenitor to $\dot{M}/v_w < 10^{-4} \frac{\text{M}_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (Mattila et al. 2005). For the normal SN Ia 2002bo, Hughes et al. (2007) used X-ray observations to constrain $\dot{M}/v_w < 2 \times 10^{-4} \frac{\text{M}_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$, assuming thermal emission dominates the X-ray signal. They also revisit a previously claimed X-ray detection of SN 2005ke (Immler et al. 2006), showing that this source is in fact not present in more carefully analyzed X-ray data. Recently, all *Swift* X-ray observations of SNe Ia to date have been stacked by Russell & Immler (2012), yielding a non-detection of $L_X < 1.7 \times 10^{38} \text{ erg s}^{-1}$ in the energy range 0.2–10 keV. Radio limits on CSM around SN 2011fe are consistent with deep *Chandra* observations obtained 4 days after explosion, which place an upper limit $\dot{M}/v_w < 2 \times 10^{-9} \frac{\text{M}_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ (Margutti et al. 2012; see also Horesh et al. 2012).

Our EVLA upper limits are a strong indication that there is not much CSM within $\sim 10^{16} \text{ cm}$ of the progenitor of SN 2011fe, consistent with a uniform density

medium of $n_{\text{CSM}} \lesssim 10 \text{ cm}^{-3}$. Similar constraints can be drawn from the morphology and X-ray emission of historical supernova remnants (SNRs) of Type Ia origin. For example, X-ray studies of SNR 0509-67.5 in the Large Magellanic Cloud and the Tycho SNR (both ~ 400 years old) imply that these SNRs are surrounded by uniform media of density $\sim 0.5\text{--}1 \text{ cm}^{-3}$ (Badenes et al. 2006, 2008), typical of the warm phase of the interstellar medium. $\text{H}\alpha$ imaging of SN 1006 with *HST* shows that this remnant is expanding into a medium of density $0.25\text{--}0.4 \text{ cm}^{-3}$, and the medium is relatively uniform, with fluctuations of $\sim 20\%$ on length scales of $\sim 1 \text{ pc}$ (Raymond et al. 2007). The youngest SNR in the Milky Way, G1.9+0.3, is likely the remnant of a SN Ia that exploded ~ 100 years ago, and is also consistent with low-density surroundings ($\sim 0.03 \text{ cm}^{-3}$; Reynolds et al. 2008; Borkowski et al. 2010; Carlton et al. 2011). This widespread consistency with our results is remarkable, as these SNRs have radii of $\sim 10^{19} \text{ cm}$, three orders of magnitude larger than the extent probed by our EVLA data.

SNRs can also shed additional light on the optically-thick accretion wind scenario, postulated by Hachisu et al. (1999) to blow from WDs that are accreting near the Eddington rate ($\gtrsim 6 \times 10^{-7} \text{ M}_\odot \text{ yr}^{-1}$). We have already shown that our radio observations can exclude such a wind in SN 2011fe if it immediately precedes the SN explosion, but in other evolutionary scenarios there may be a delay between the production of the wind and the SN of $\sim 10^5\text{--}10^6$ years (Han & Podsiadlowski 2004). In this case, a large cavity will surround the WD at the time of SN Ia explosion, with a radius of $\sim 10 \text{ pc}$ and $n_{\text{CSM}} \lesssim 10^{-3} \text{ cm}^{-3}$ (Badenes et al. 2007), and the outer edge of this cavity will be marked by a dense shell with $n_{\text{CSM}} \approx 100 \text{ cm}^{-3}$. This scenario would yield radio non-detections at early times, as we observe, but would also leave a clear imprint on SNRs, wherein SNRs should have larger radii and faster expansion velocities than expected for typical interstellar medium densities. Such an effect is not observed in a sample of seven Type Ia SNRs (Badenes et al. 2007); combined with our early time observations, this implies that accretion winds can not play a major role in the progenitor systems of most SNe Ia. An interaction with the warm phase of the interstellar medium seems to be able to explain the properties of most Type Ia SNRs.

Another intriguing constraint on the CSM surrounding SNe Ia comes from high-resolution optical spectroscopy, as observations of time-variable narrow Na I D absorption lines in the spectra of SNe Ia (Patat et al. 2007a; Blondin et al. 2009; Simon et al. 2009; Sternberg et al. 2011). Assuming that the variations in time are due to ionization by the SN light followed by gradual recombination, the distance to the absorbing material can be estimated at $\gtrsim 10^{17} \text{ cm}$ with a mass of $10^{-5}\text{--}10^{-2} \text{ M}_\odot$, depending on its geometry and clumpiness (Chugai 2008; Simon et al. 2009). This distribution of material may be consistent with old nova shells from a recurrent nova (similar absorption features were observed following the 2006 outburst of RS Oph by Patat et al. 2011a. However, U Sco did not show time-variable absorption lines during its 2010 outburst; Kafka & Williams 2011). We note that in the case of SN 2006X (the first published

SN Ia with recognized time-variable Na I D lines), VLA observations were acquired and yielded a non-detection, constraining $\dot{M}/v_w \lesssim 3 \times 10^{-7} \frac{M_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$ at a distance of $\sim 10^{17}$ cm (Patat et al. 2007a, using the models described here).

As we have shown, early-time radio observations can only rule out some of the parameter space associated with recurrent novae, and the observations presented here are sensitive to material at radii $\lesssim 10^{16}$ cm, so high-resolution optical spectroscopy is a complementary strategy for probing the CSM at all scales. No time-variable optical absorption lines are apparent in SN 2011fe (Patat et al. 2011b), consistent with an absence of CSM. We note that preliminary statistics hint that roughly half of SNe Ia occur in similarly “clean” environments, while $\sim 25\%$ of SNe Ia in spiral galaxies show narrow blue-shifted absorption lines (Sternberg et al. 2011). If all SN Ia systems that show blue-shifted absorption lines have recurrent nova progenitors, this would conflict with our census of recurrent novae in the local universe, predicting many more nova explosions than are observed (della Valle & Livio 1996).

We emphasize, however, that the progenitors of SNe Ia may be diverse, and constraints placed on the progenitor of SN 2011fe will not necessarily hold for the entire class of SNe Ia. For example, while most observations of SN Ia remnants are not consistent with accretion winds (Badenes et al. 2007), this does not imply that all SN Ia progenitor systems do not host accretion winds. For one, RCW 86 may provide a counter example, as recent work shows that it is likely expanding into a wind-blown cavity (Williams et al. 2011); however, it remains uncertain if RCW 86 is a SN Ia or core-collapse remnant. Also, many SNe Ia do not show time-variable Na I D absorption lines (Patat et al. 2007b; Simon et al. 2007; Sternberg et al. 2011) including SN 2011fe (Patat et al. 2011b). This overall diversity could be due to viewing angle effects, differences in metallicity of the CSM, or a range of circumbinary environments in the progenitor system.

6.2. Directly Detecting the Binary Companions of SNe Ia

While it is possible to directly detect the massive progenitor stars of core-collapse SNe in nearby galaxies using archival pre-explosion optical images (Smartt 2009), both the massive WDs that produce SNe Ia and their binary companions are too faint to be detected in external galaxies (Maoz & Mannucci 2008). Indeed, no optical source was detected pre-explosion at the position of SN 2011fe (Li et al. 2011b). However, in our Galaxy, we can search Type Ia SNRs for stars with unusual proper motions and abundances, as might be expected for the binary companion of the now-destroyed WD. One such star was proposed to be the sub-giant star G in the Tycho SNR (Ruiz-Lapuente et al. 2004), but more recently star G’s affiliation with the SNR has been called into question (Kerzendorf et al. 2009). Additional studies are required, of Tycho and other SNRs in the Milky Way and Magellanic Clouds, to directly search for binary companions to SNe Ia.

When the SN shockwave plows over a non-degenerate companion, this interaction may leave an observable

mark upon the SN Ia explosion itself. If the binary has a relatively small separation, some of the companion star’s envelope should be entrained in the SN ejecta, and become detectable in late-time nebular spectra as H α emission (Marietta et al. 2000). Deep limits have been placed on the presence of such emission, implying that $< 0.01 M_\odot$ of hydrogen-rich material is swept from a companion star, and presenting a challenge to progenitor scenarios where the companion is filling its Roche lobe (Leonard 2007). The interaction may also be detectable as an early-time blue component in the optical SN light curve (Kasen 2010); the magnitude of this early component will depend on viewing angle and the nature of the companion, with Roche-lobe filling red giant stars producing the brightest signature. In the significant samples of SNe Ia now available, this effect has never been detected, implying that $< 20\%$ of SNe Ia have red giant companions (Hayden et al. 2010; Bianco et al. 2011; Brown et al. 2012). In addition, no blue early-time blue component was detected for SN 2011fe, placing strong constraints on possible Roche-lobe filling companions ($< 1 M_\odot$ red giant, or $< 3 M_\odot$ main sequence; Brown et al. 2011; see also Nugent et al. 2011; Bloom et al. 2012).

7. CONCLUSIONS

Using deep EVLA radio observations, we have shown that the progenitor system of SN 2011fe did not host a red giant secondary or a wind-producing high accretion rate. We also rule out a significant fraction of the parameter space for stably burning WD or recurrent nova progenitors—constraints that are bolstered by pre-explosion *Chandra* and HST imaging and a lack of an early-time blue component in the optical light curve.

Our study may be viewed as consistent with the growing body of evidence favoring DD progenitors, which includes measurements of the delay time distribution of SNe Ia (Maoz et al. 2010) and computational successes with theoretical DD explosions (Pakmor et al. 2010). However, a recent preliminary model of a WD–WD merger suggests the presence of dense circumbinary medium Shen et al. (2011), which could be constrained by these and future radio observations. A thorough treatment of this scenario would require a re-evaluation of the SN shockwave dynamics, as it is predicted that a dense envelope of material will surround the primary WD at small radius ($\sim 0.1 M_\odot$ at $\lesssim 10^{13}$ cm), which would slow the shockwave. At larger radius, the WD is surrounded by a $\rho_{\text{CSM}} \propto r^{-2}$ wind profile, expelling roughly $\sim 0.1 M_\odot$ over 10^4 years at a velocity of $\sim 100 \text{ km s}^{-1}$, producing a relatively high $\dot{M}/v_w \approx 10^{-5} \frac{M_\odot \text{ yr}^{-1}}{100 \text{ km s}^{-1}}$. It is the interaction between this wind and the SN shockwave that would likely produce detectable radio emission, but more detailed models of the density profile and mass loss in DD systems are needed to understand the velocity evolution of the shockwave and the predicted synchrotron signal.

More exotic scenarios, like spin-up/spin-down models (Justham 2011; Di Stefano et al. 2011) or the core-degenerate scenario (Ilkov & Soker 2012), with a significant delay between mass loss and explosion ($\gtrsim 10^5$ years) are also not excluded. While our EVLA upper limits place the most stringent constraints to date on the CSM density around a SN Ia, and our analysis indicates that

most SD progenitor models are ruled out, detailed studies (theoretical and observational) of the circumbinary environments surrounding accreting WDs are required to further shed light on their connection to Type Ia SNe.

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REFERENCES

- Badenes, C., Borkowski, K. J., Hughes, J. P., Hwang, U., & Bravo, E. 2006, *ApJ*, 645, 1373
- Badenes, C., Hughes, J. P., Bravo, E., & Langer, N. 2007, *ApJ*, 662, 472
- Badenes, C., Hughes, J. P., Cassam-Chenaï, G., & Bravo, E. 2008, *ApJ*, 680, 1149
- Berger, E., Kulkarni, S. R., & Chevalier, R. A. 2002, *ApJ*, 577, L5
- Berger, E., Kulkarni, S. R., Frail, D. A., & Soderberg, A. M. 2003, *ApJ*, 599, 408
- Bianco, F. B., Howell, D. A., Sullivan, M., et al. 2011, *ApJ*, 741, 20
- Blondin, S., Prieto, J. L., Patat, F., et al. 2009, *ApJ*, 693, 207
- Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, *ApJ*, 744, L17
- Borkowski, K. J., Reynolds, S. P., Green, D. A., et al. 2010, *ApJ*, 724, L161
- Brown, P. J., Dawson, K. S., Harris, D. W., et al. 2012, *ApJ*, in press
- Brown, P. J., Dawson, K. S., de Pasquale, M., et al. 2011, *arXiv* 1110.2538
- Carlton, A. K., Borkowski, K. J., Reynolds, S. P., et al. 2011, *ApJ*, 737, L22
- Chen, X., Han, Z., & Tout, C. A. 2011, *ApJ*, 735, L31+
- Chevalier, R. A. 1982a, *ApJ*, 258, 790
- . 1982b, *ApJ*, 259, 302
- . 1998, *ApJ*, 499, 810
- Chevalier, R. A., & Fransson, C. 2006, *ApJ*, 651, 381
- Chomiuk, L., & Soderberg, A. 2011, *ATel*, 3597, 1
- Chugai, N. N. 2008, *Astronomy Letters*, 34, 389
- Colgate, S. A. 1970, in *Proc. of the 11th International Cosmic Ray Conference*, 353
- Cowley, A. P., Schmidtke, P. C., Crampton, D., & Hutchings, J. B. 1998, *ApJ*, 504, 854
- Dale, D. A., Cohen, S. A., Johnson, L. C., et al. 2009, *ApJ*, 703, 517
- della Valle, M., & Livio, M. 1996, *ApJ*, 473, 240
- Deufel, B., Barwig, H., Šimić, D., Wolf, S., & Drory, N. 1999, *A&A*, 343, 455
- Di Stefano, R., Voss, R., & Claeys, J. S. W. 2011, *ApJ*, 738, L1
- Diaz, M. P., Williams, R. E., Luna, G. J., Moraes, M., & Takeda, L. 2010, *AJ*, 140, 1860
- Duschl, W. J., Livio, M., & Truran, J. W. 1990, *ApJ*, 360, 232
- Evans, A., Krautter, J., Vanzì, L., & Starrfield, S. 2001, *A&A*, 378, 132
- Ferrière, K. M. 2001, *Reviews of Modern Physics*, 73, 1031
- Fruchter, A. S., Levan, A. J., Strolger, L., et al. 2006, *Nature*, 441, 463
- Hachisu, I., Kato, M., Kato, T., & Matsumoto, K. 2000, *ApJ*, 528, L97
- Hachisu, I., Kato, M., & Nomoto, K. 1999, *ApJ*, 522, 487
- Han, Z., & Podsiadlowski, P. 2004, *MNRAS*, 350, 1301
- Hancock, P. P., Gaensler, B. M., & Murphy, T. 2011, *ApJ*, 735, L35
- Hayden, B. T., Garnavich, P. M., Kasen, D., et al. 2010, *ApJ*, 722, 1691
- Hillebrandt, W., & Niemeyer, J. C. 2000, *ARA&A*, 38, 191
- Hoopes, C. G., Walterbos, R. A. M., & Bothun, G. D. 2001, *ApJ*, 559, 878
- Horesh, A., Kulkarni, S. R., Fox, D. B., et al. 2012, *ApJ*, 746, 21
- Huang, R.-Q., & Yu, K. N. 1996, *Chinese Journal of Astronomy & Astrophysics*, 20, 175
- Hughes, J. P., Chugai, N., Chevalier, R., Lundqvist, P., & Schlegel, E. 2007, *ApJ*, 670, 1260
- Iben, Jr., I., & Tutukov, A. V. 1984, *ApJS*, 54, 335
- Ilkov, M., & Soker, N. 2012, *MNRAS*, 419, 1695
- Immler, S., Brown, P. J., Milne, P., et al. 2006, *ApJ*, 648, L119
- Justham, S. 2011, *ApJ*, 730, L34+
- Kafka, S., & Williams, R. 2011, *A&A*, 526, A83
- Kasen, D. 2010, *ApJ*, 708, 1025
- Kelly, P. L., Kirshner, R. P., & Pahre, M. 2008, *ApJ*, 687, 1201
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- Kerzendorf, W. E., Schmidt, B. P., Asplund, M., et al. 2009, *ApJ*, 701, 1665
- Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, *PASP*, 121, 1395
- Leonard, D. C. 2007, *ApJ*, 670, 1275
- Li, W., Chornock, R., Leaman, J., et al. 2011a, *MNRAS*, 412, 1473
- Li, W., Bloom, J. S., Podsiadlowski, P., et al. 2011b, *Nature*, 480, 348
- Liu, J., Di Stefano, R., Wang, T., & Moe, M. 2011, *arXiv* 1110.2506
- Maoz, D., & Mannucci, F. 2008, *MNRAS*, 388, 421
- Maoz, D., Sharon, K., & Gal-Yam, A. 2010, *ApJ*, 722, 1879
- Margutti, R., Soderberg, A. M., Chomiuk, L., et al. 2012, *arXiv* 1202.0741
- Marietta, E., Burrows, A., & Fryxell, B. 2000, *ApJS*, 128, 615
- Mattila, S., Lundqvist, P., Sollerman, J., et al. 2005, *A&A*, 443, 649
- Matzner, C. D., & McKee, C. F. 1999, *ApJ*, 510, 379
- Mazzali, P. A., Röpke, F. K., Benetti, S., & Hillebrandt, W. 2007, *Science*, 315, 825
- Mohamed, S., & Podsiadlowski, P. 2011, in *Asymmetric Planetary Nebulae 5 Conf.*, ed. A. Zijlstra, F. Lykou, I. McDonald, & E. Lagadec
- Murray, N. 2002, in *ASP Conf. Ser.*, Vol. 261, *The Physics of Cataclysmic Variables and Related Objects*, ed. B. T. Gänsicke, K. Beuermann, & K. Reinsch, 308
- Nakar, E., & Sari, R. 2012, *ApJ*, 747, 88
- Nomoto, K. 1982, *ApJ*, 253, 798
- Nomoto, K., Saio, H., Kato, M., & Hachisu, I. 2007, *ApJ*, 663, 1269
- Nugent, P. E., Sullivan, M., Cenko, S. B., et al. 2011, *Nature*, 480, 344
- Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, *Nature*, 463, 61
- Panagia, N., Van Dyk, S. D., Weiler, K. W., et al. 2006, *ApJ*, 646, 369
- Patat, F., Chugai, N. N., Podsiadlowski, P., et al. 2011a, *A&A*, 530, A63+
- Patat, F., Chandra, P., Chevalier, R., et al. 2007a, *Science*, 317, 924
- Patat, F., Benetti, S., Justham, S., et al. 2007b, *A&A*, 474, 931
- Patat, F., Cordiner, M. A., Cox, N. L. J., et al. 2011b, *arXiv* 1112.0247
- Perley, R. A., Chandler, C. J., Butler, B. J., & Wrobel, J. M. 2011, *ApJ*, 739, L1+
- Raymond, J. C., Korreck, K. E., Sedlacek, Q. C., et al. 2007, *ApJ*, 659, 1257
- Readhead, A. C. S. 1994, *ApJ*, 426, 51
- Reynolds, S. P., Borkowski, K. J., Green, D. A., et al. 2008, *ApJ*, 680, L41
- Ruiz-Lapuente, P., Comeron, F., Méndez, J., et al. 2004, *Nature*, 431, 1069
- Russell, B. R., & Immler, S. 2012, *ApJ*, in press
- Schaefer, B. E. 2010, *ApJS*, 187, 275
- Seaquist, E. R., & Taylor, A. R. 1990, *ApJ*, 349, 313
- Shappee, B. J., & Stanek, K. Z. 2011, *ApJ*, 733, 124
- Shen, K. J., & Bildsten, L. 2007, *ApJ*, 660, 1444
- . 2009, *ApJ*, 692, 324
- Shen, K. J., Bildsten, L., Kasen, D., & Quataert, E. 2011, *arXiv* 1108.4036
- Simon, J. D., Gal-Yam, A., Penprase, B. E., et al. 2007, *ApJ*, 671, L25
- Simon, J. D., Gal-Yam, A., Gnat, O., et al. 2009, *ApJ*, 702, 1157
- Smartt, S. J. 2009, *ARA&A*, 47, 63
- Soderberg, A. M., Chakraborti, S., Pignata, G., et al. 2010, *Nature*, 463, 513
- Soderberg, A. M., Margutti, R., Zauderer, B. A., et al. 2011, *arXiv* 1107.1876

- Sternberg, A., Gal-Yam, A., Simon, J. D., et al. 2011, *Science*, 333, 856
- Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, *AJ*, 136, 2563
- Webbink, R. F. 1984, *ApJ*, 277, 355
- Weiler, K. W., Panagia, N., Montes, M. J., & Sramek, R. A. 2002, *ARA&A*, 40, 387
- Whelan, J., & Iben, Jr., I. 1973, *ApJ*, 186, 1007
- Williams, B. J., Blair, W. P., Blondin, J. M., et al. 2011, *ApJ*, 741, 96
- Williams, R., Mason, E., Della Valle, M., & Ederoclite, A. 2008, *ApJ*, 685, 451
- Wood-Vasey, W. M., & Sokoloski, J. L. 2006, *ApJ*, 645, L53
- Yaron, O., Prialnik, D., Shara, M. M., & Kovetz, A. 2005, *ApJ*, 623, 398
- Zhang, W., MacFadyen, A., & Wang, P. 2009, *ApJ*, 692, L40